Challenges with %-level CMB lensing science

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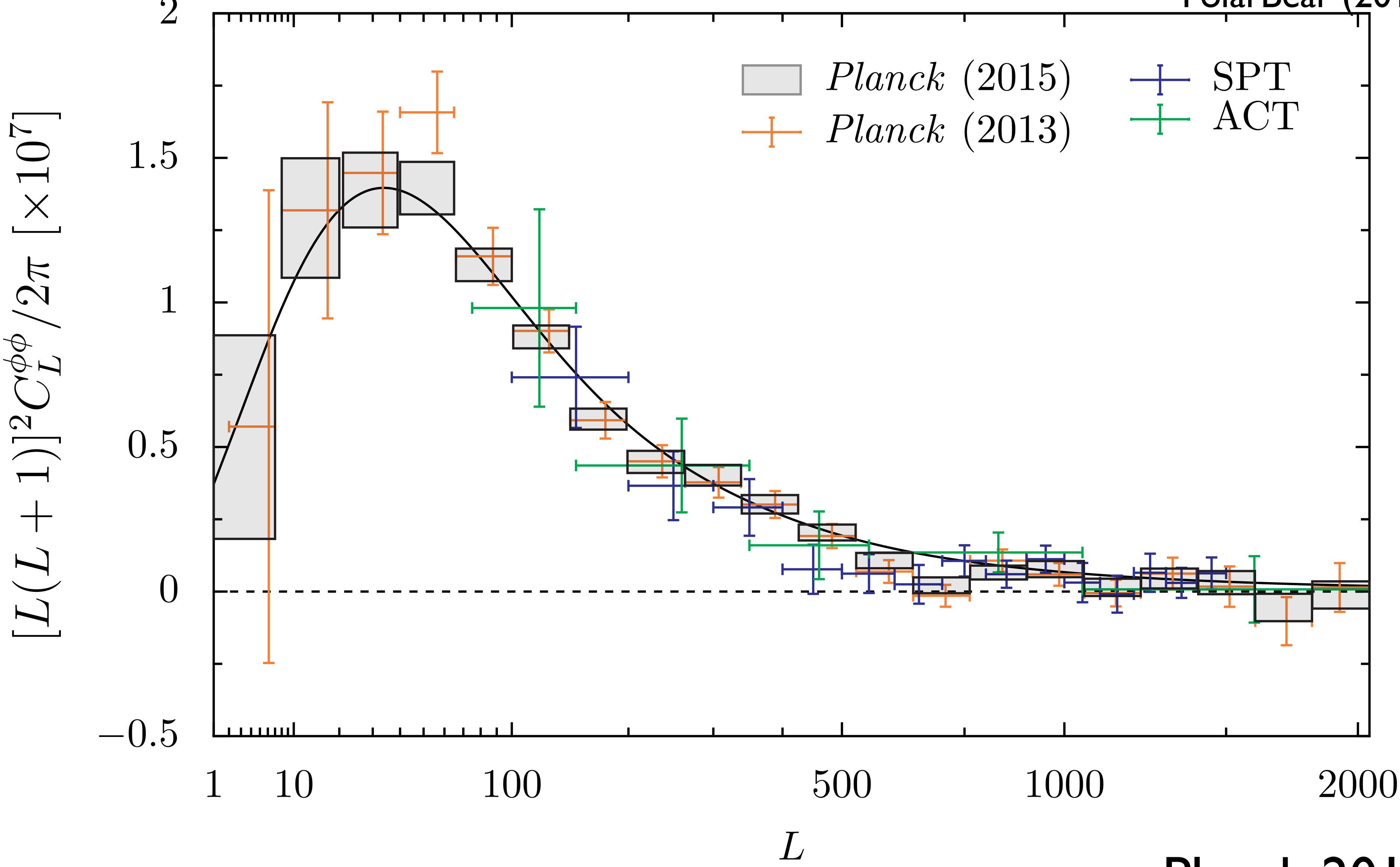
Lensing autospectrum current state-of-the-art

Also: SPTpol (Story+ 2015)
PolarBear (2015)



Planck 2015

Timeline of CMB experiments

Abazajian+ 2014
(Snowmass white
paper)

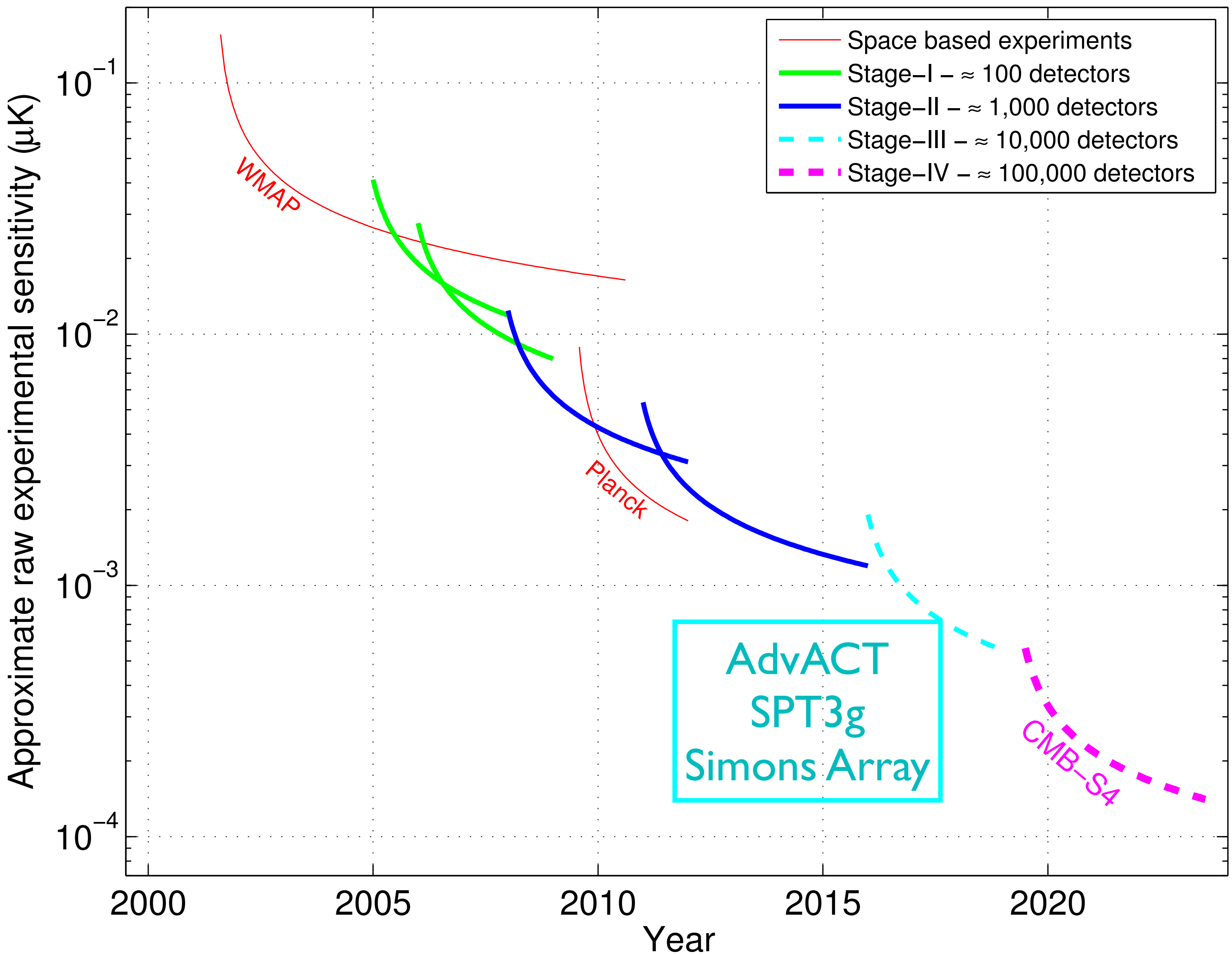
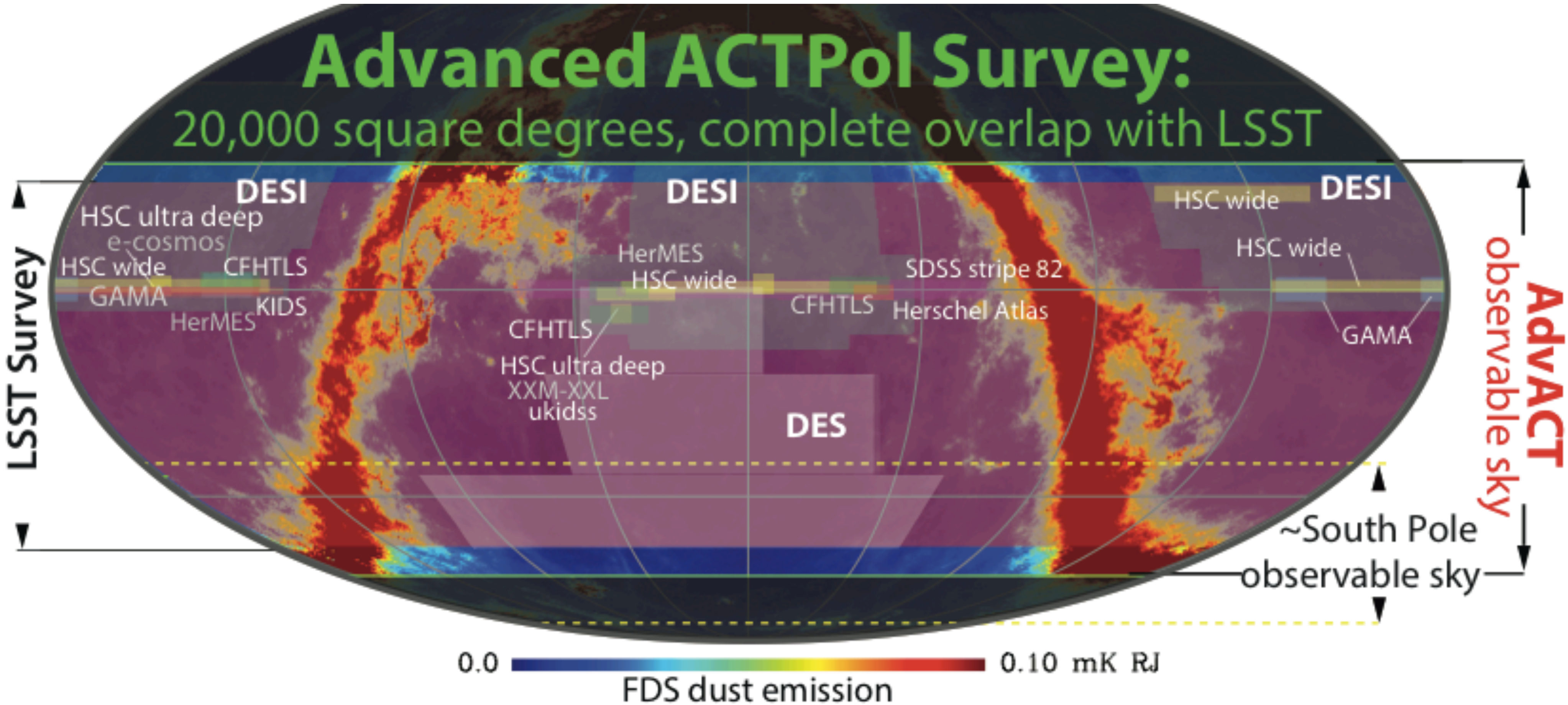


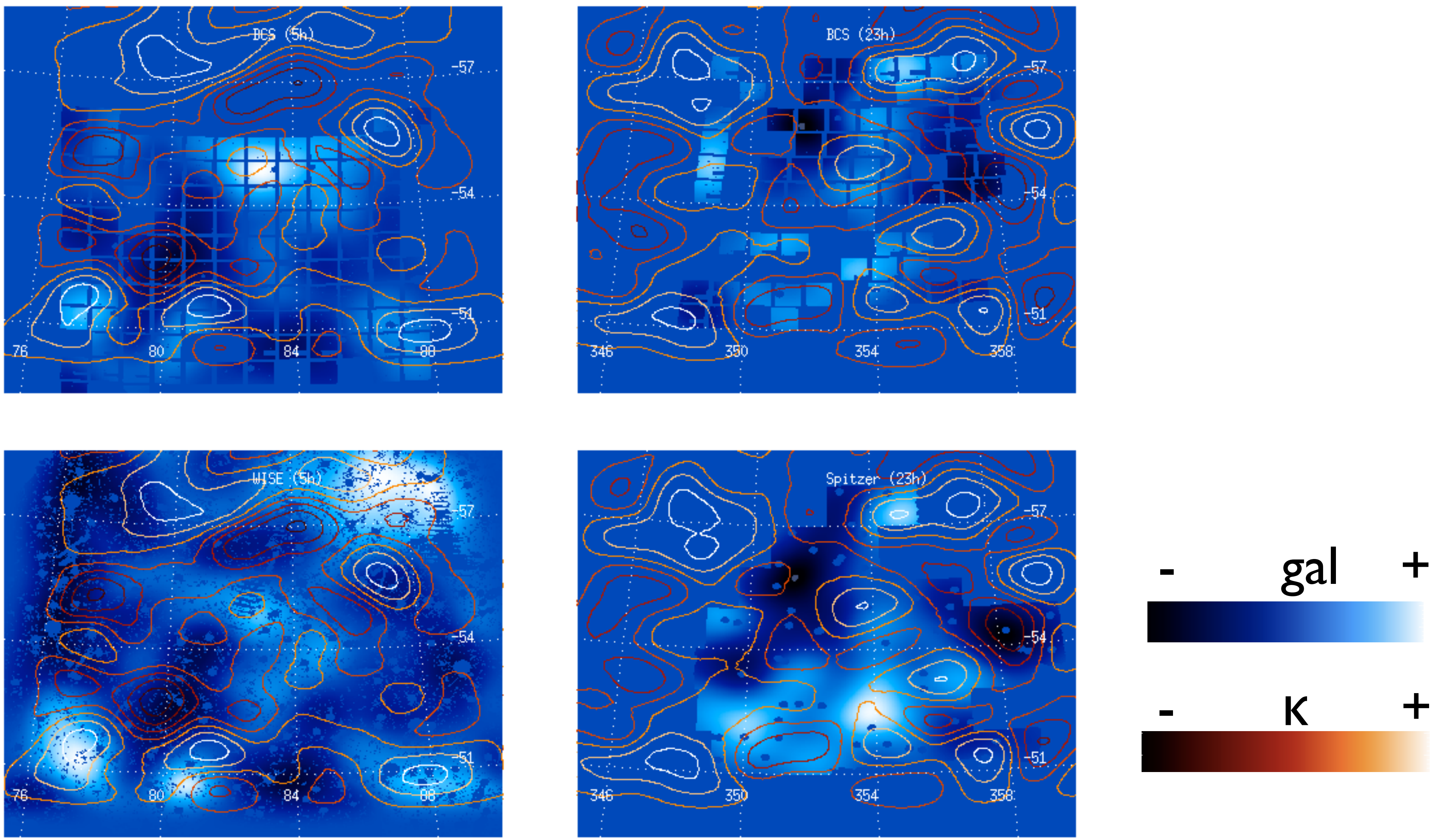
Figure 6. *Plot illustrating the evolution of the raw sensitivity of CMB experiments, which scales as the total number of bolometers. Ground-based CMB experiments are classified into Stages with Stage II experiments having $O(1000)$ detectors, Stage III experiments having $O(10{,}000)$ detectors, and a Stage IV experiment (such as CMB-S4) having $O(100{,}000)$ detectors.*



- Half the sky
- 5 frequencies
- Map sensitivity 5x better than *Planck*
- Spatial resolution 5x better than *Planck*

- After that: SO, S4

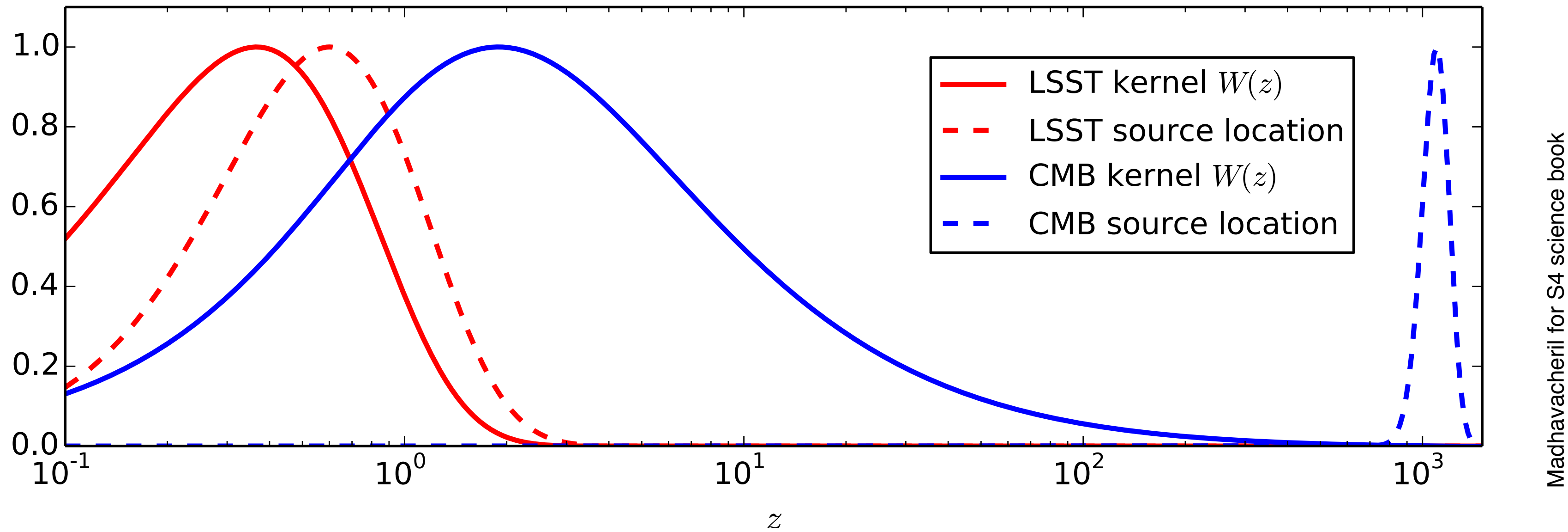
Galaxy and κ maps, overlaid



- All smoothed to 1° scales

Bleem, van Engelen, Holder, et al 2012

Cross-correlation applications



$<\kappa_{CMB}\ \delta_{gal}>$

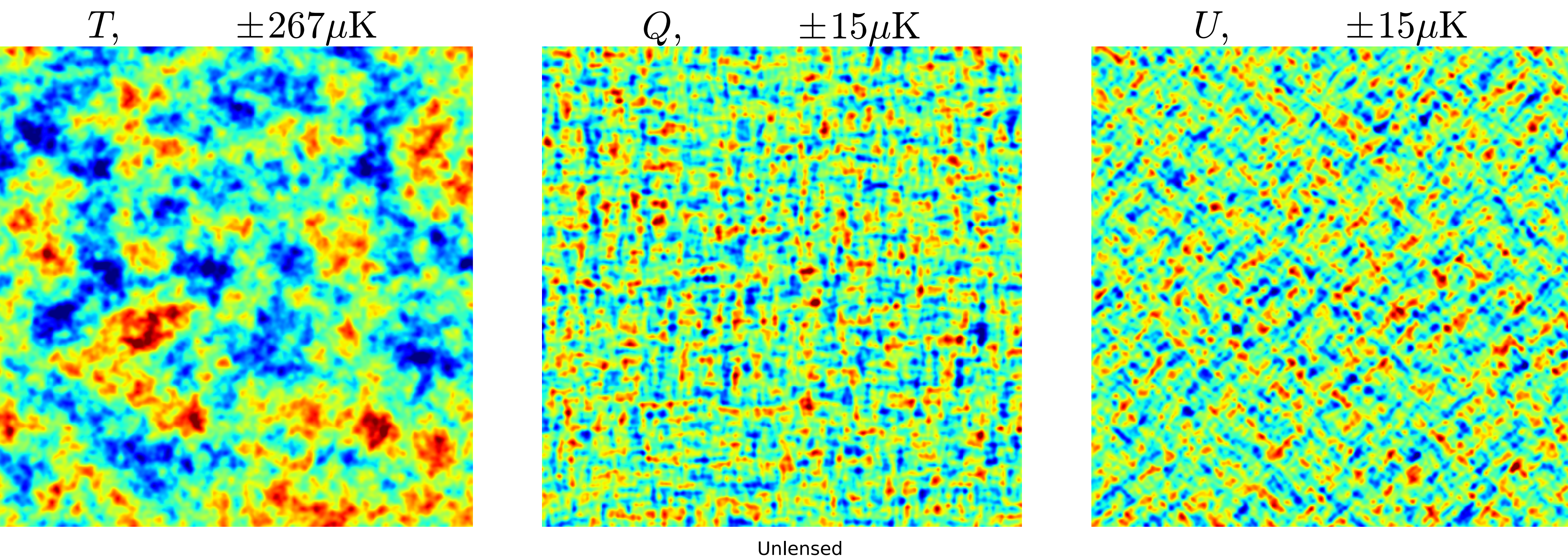
- $b_{gal}(z)$
- Distance ratios with multiple sources
- Calibrating multiplicative shear biases
- Independent measure of m_ν?

$<\kappa_{CMB}\ \kappa_{gal}>$

- Mass tomography with long lever arm
- Calibrating shear intrinsic alignments
- Calibrating multiplicative shear biases

Unlensed

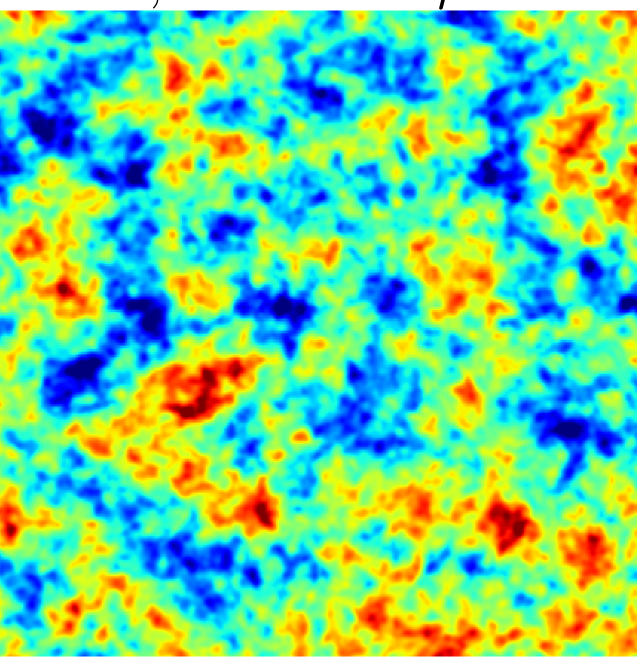
10° x 10°



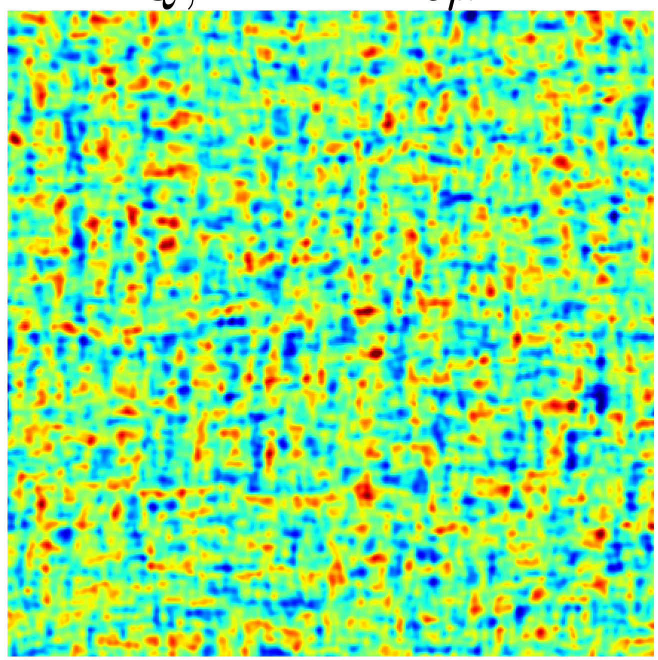
Lensed

10° x 10°

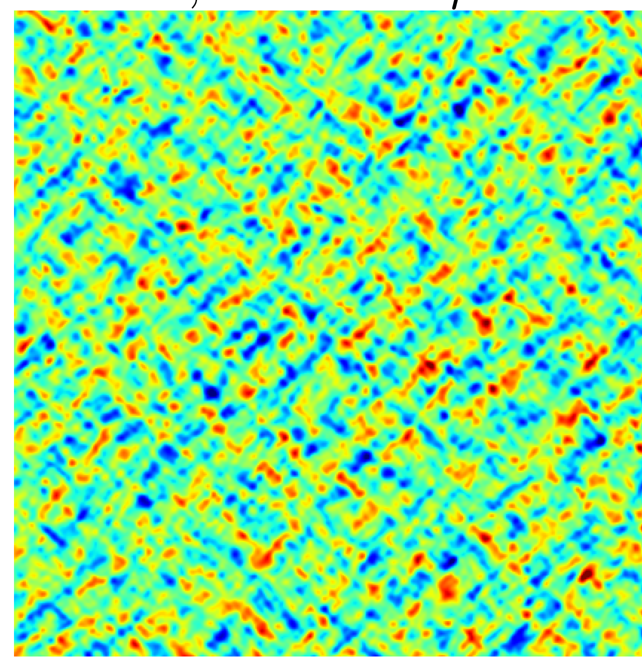
$T, \qquad \pm 267\mu\mathrm{K}$



$Q, \qquad \pm 15\mu\mathrm{K}$

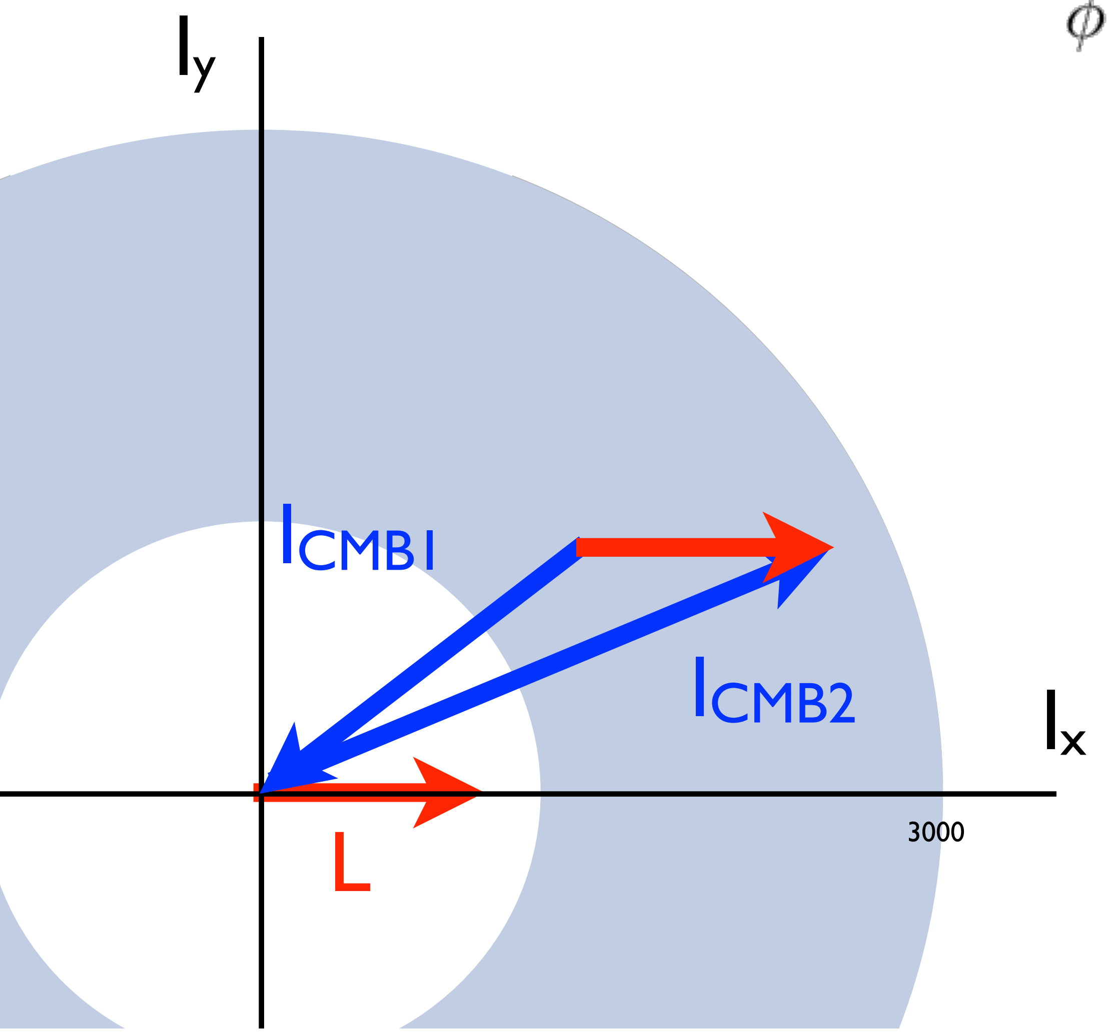


$U, \qquad \pm 15\mu\mathrm{K}$



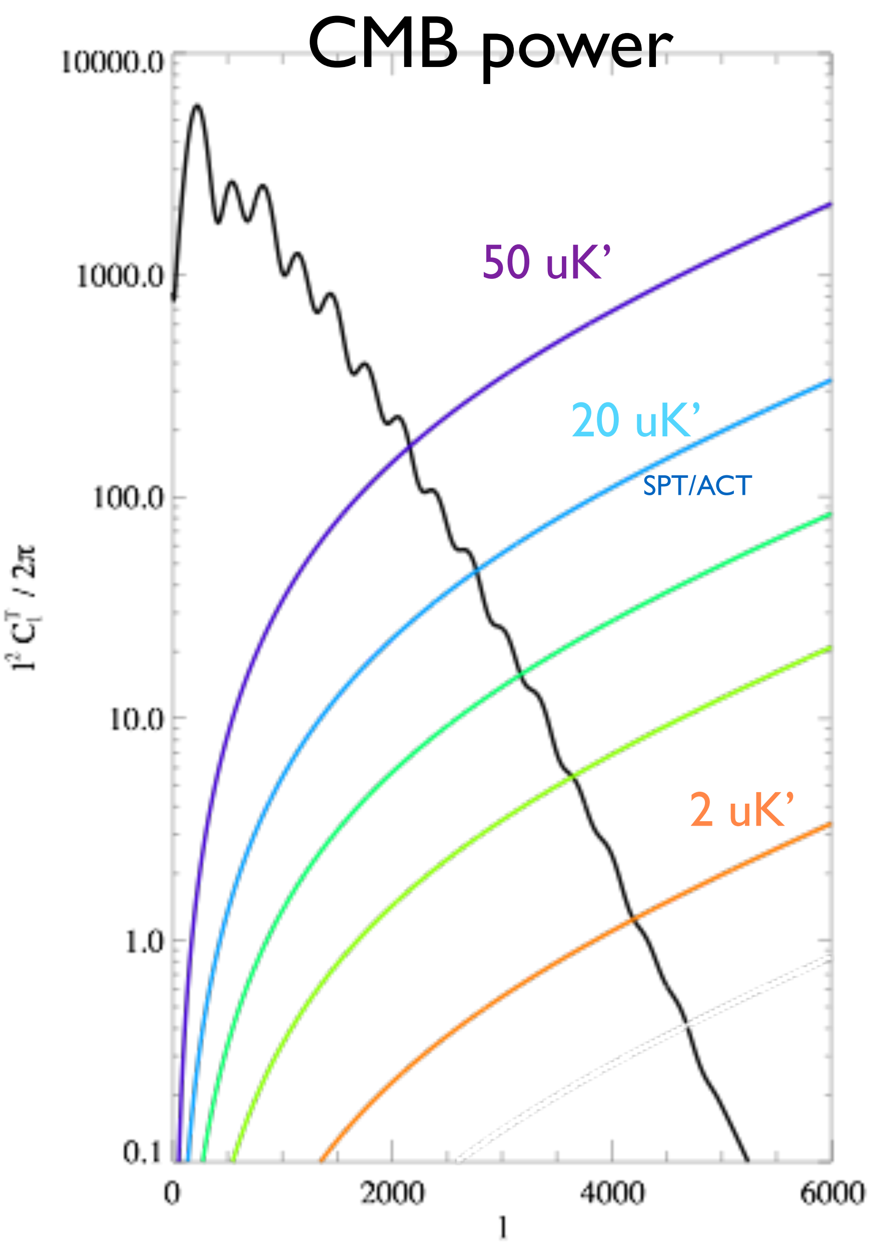
Lensed

Quadratic estimator

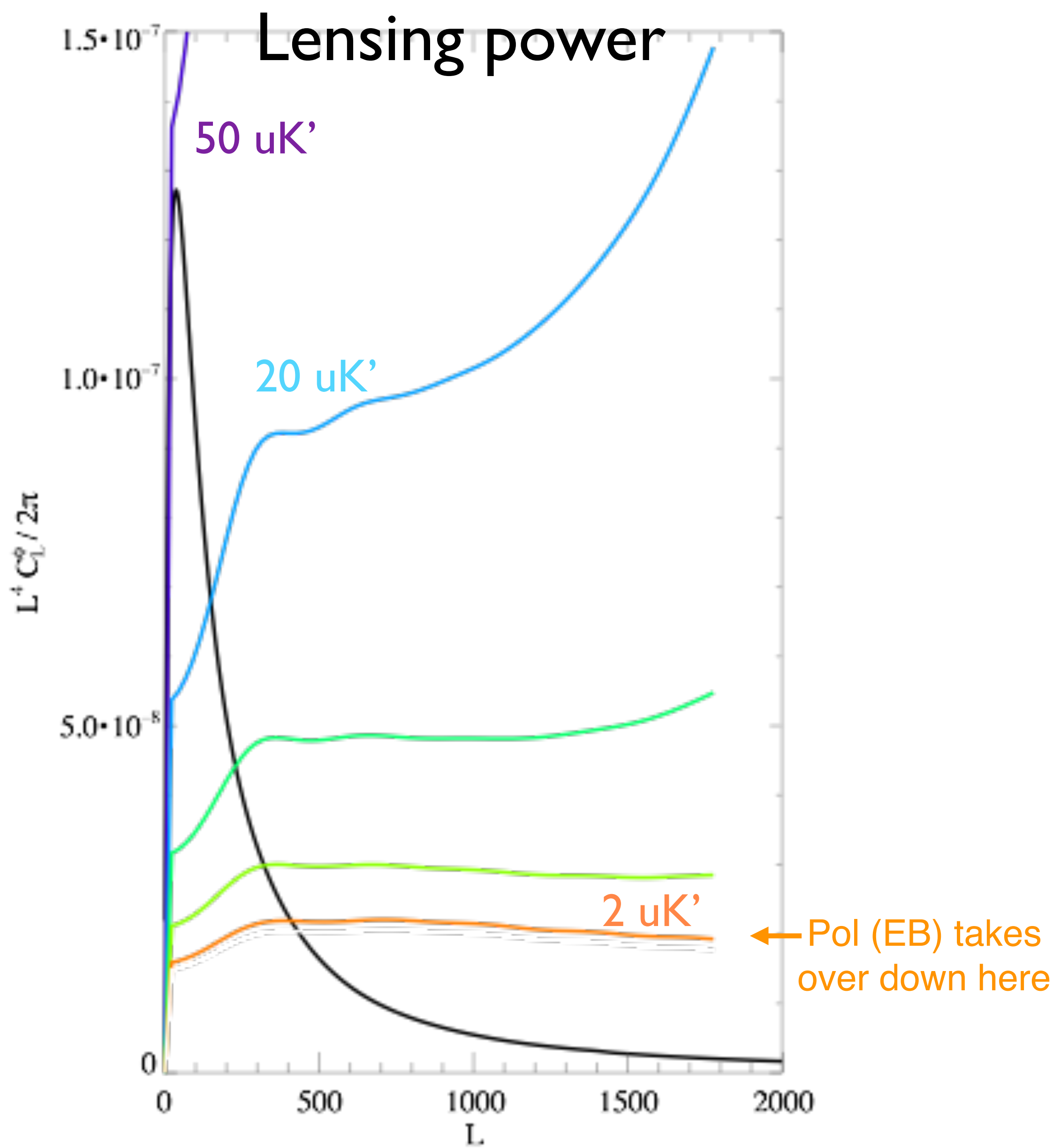


$$\hat{\phi}(\mathbf{L}) \sim \sum_{l} X(\mathbf{l}) X'(\mathbf{L}-\mathbf{l})$$

X, X' $\in$ {T, E, B}



Noise per mode in CMB

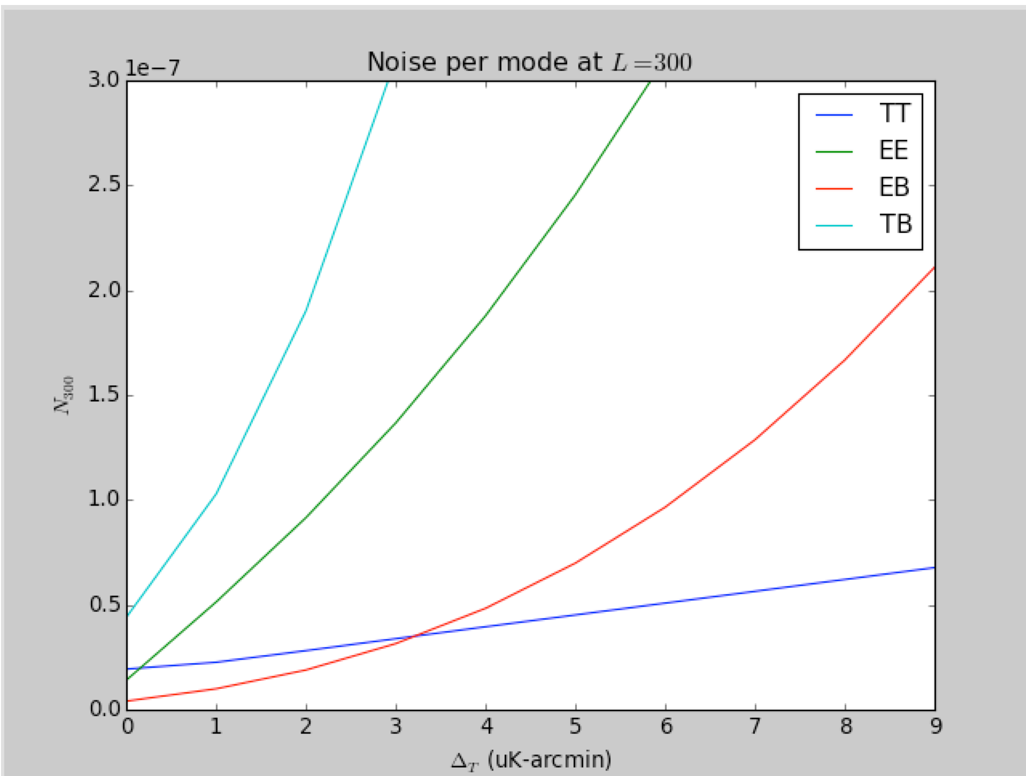


Noise per mode in reconstructed lensing field

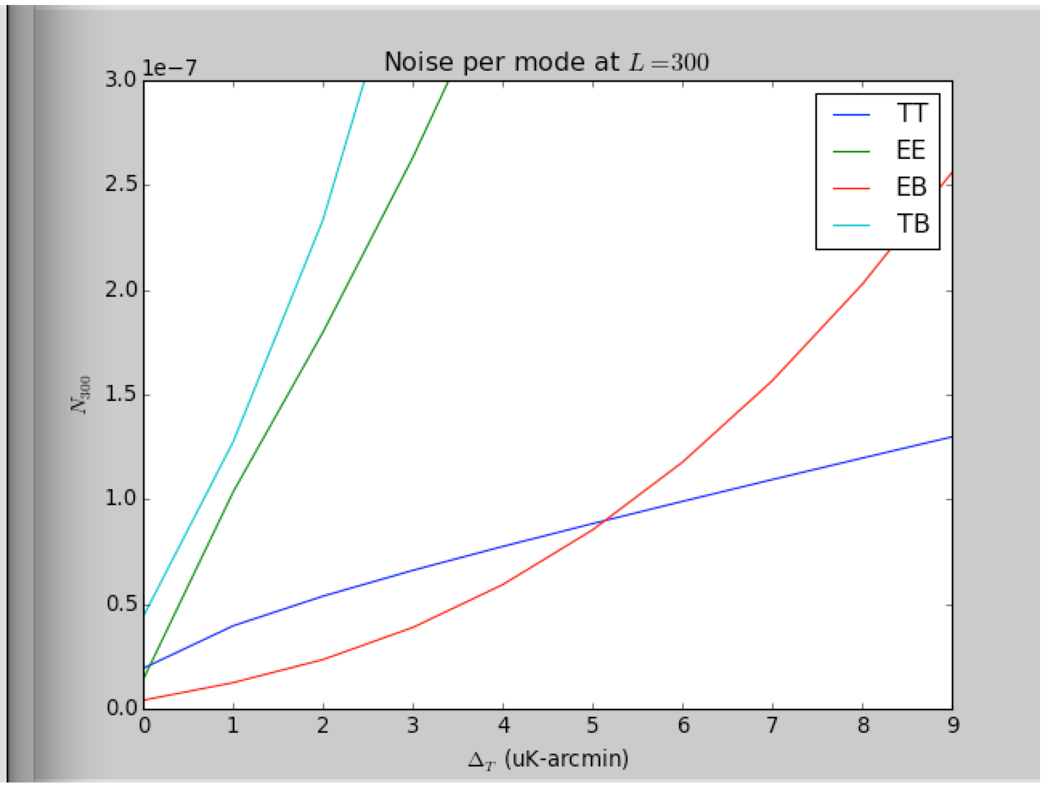
Set by $1/(l_{max})^2$

- Temperature-dominated — for time being
- Statistical error dominated — for time being

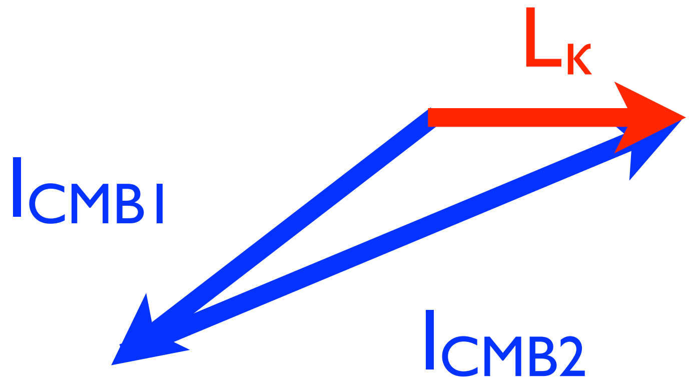
1.4’ beam



4’ beam



Foreground biases to cross-correlation



$\langle \kappa g \rangle$

Temperature

- SZ
- CIB

- Clustered
- Poisson

$\langle TTg \rangle$

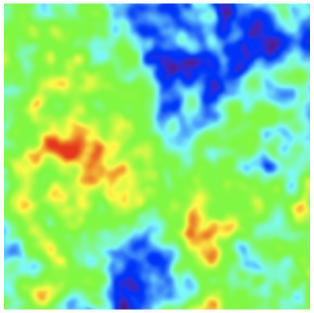
Polarization

- Polarized sources (Poisson)

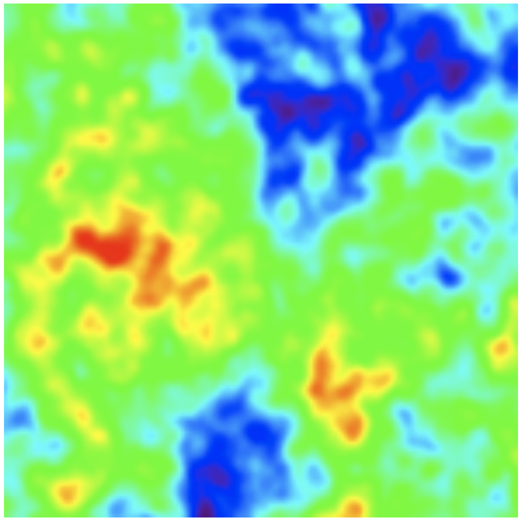
$\langle EBg \rangle$

Foreground "correlatedness" bias

At a local overdensity of lensing mass, CMB stretches out:



Unlensed



Lensed

But also a local excess of variance from tracers

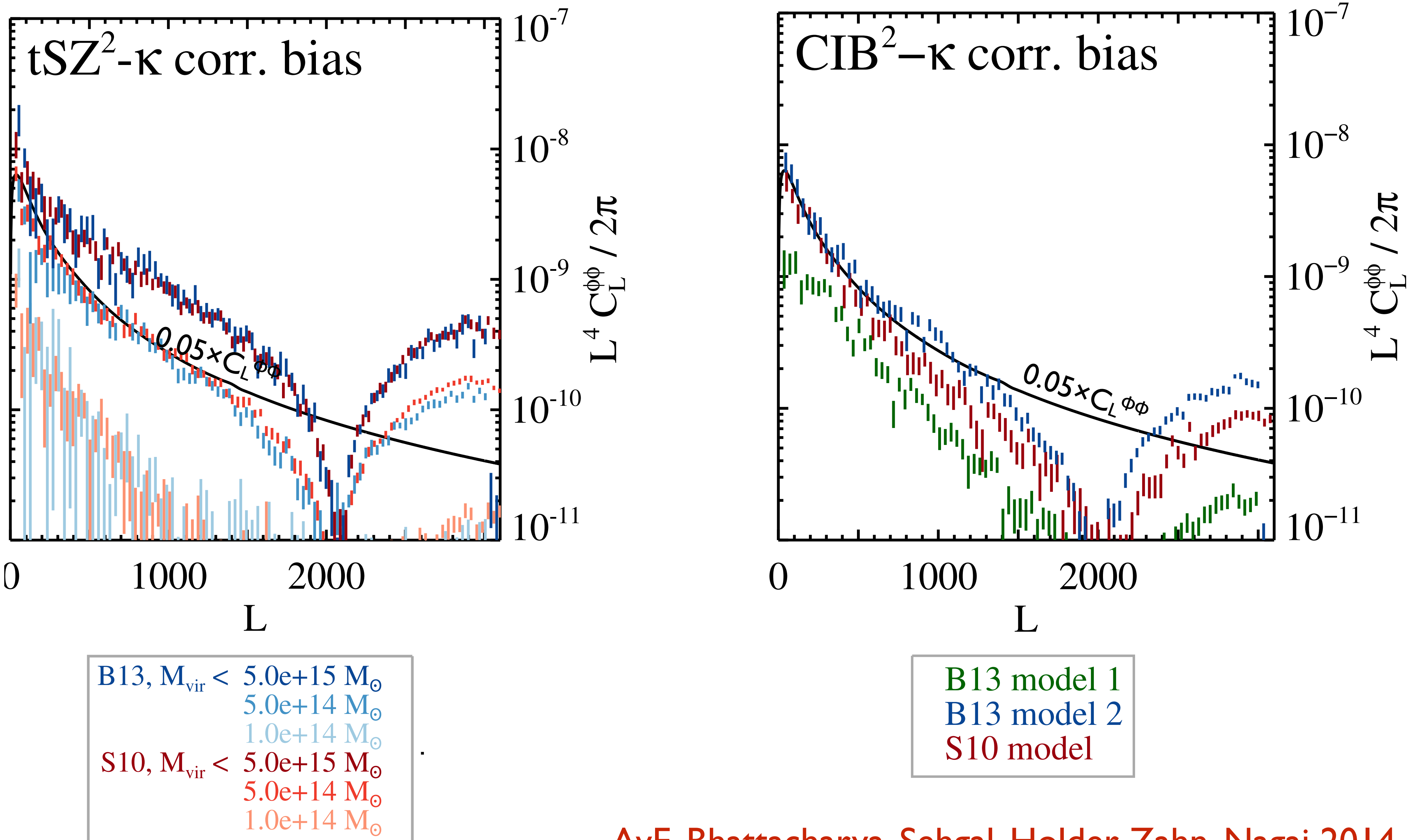
$\Longrightarrow$ Missing CMB fluctuation "filled in" with tracers

$\Longrightarrow$ Less lensing inferred

Sensitive to <S S κ> bispectrum

Foreground biases

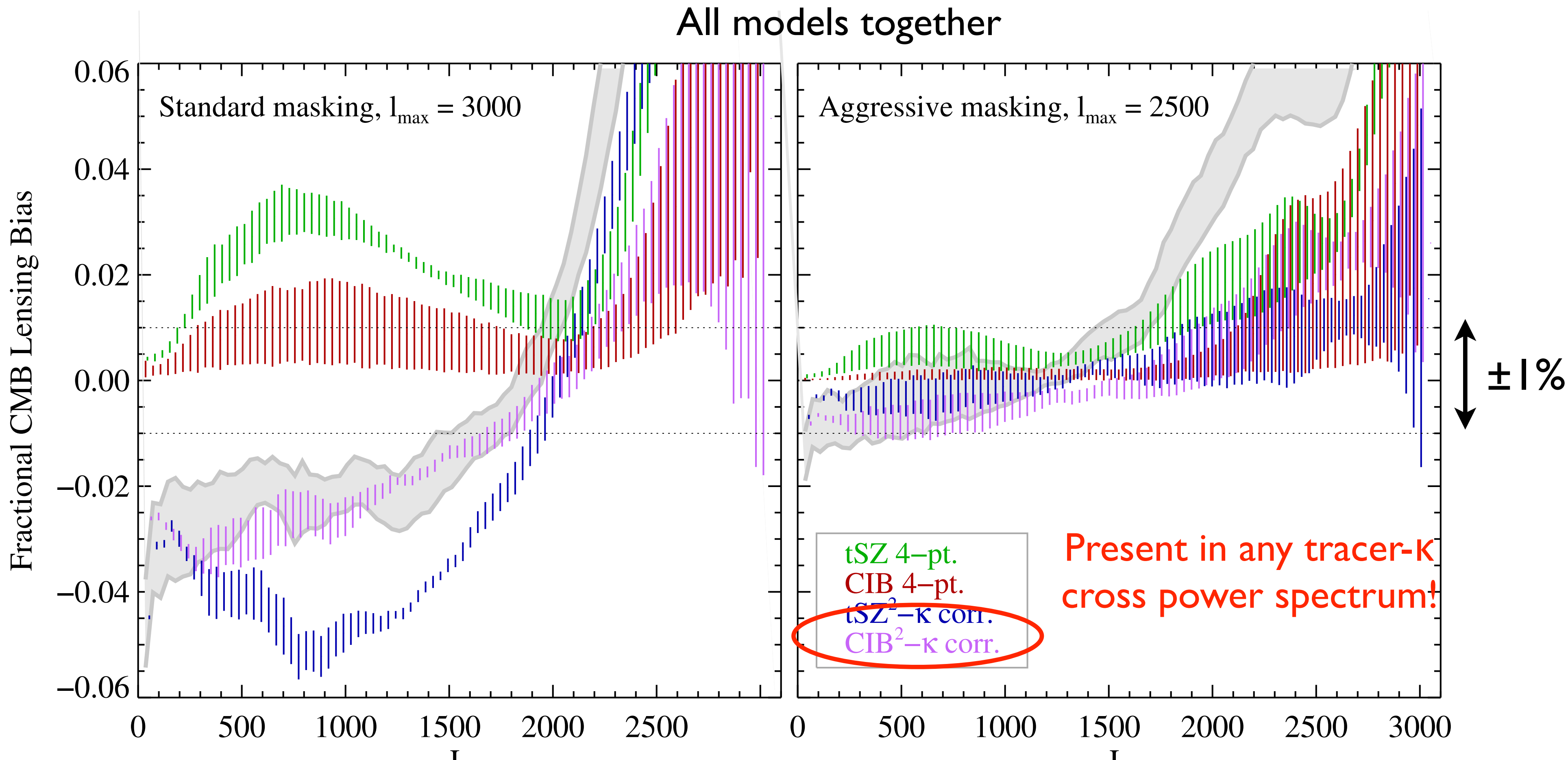
from temperature at one frequency (150 GHz)



AvE, Bhattacharya, Sehgal, Holder, Zahn, Nagai 2014

Foreground biases

from temperature at one frequency (150 GHz)



Sources to 5 mJy
Clusters to 5e14 M_{sun}
l_{max} = 3000

Sources to 1 mJy
Clusters to 1e14 M_{sun}
l_{max} = 2500

AvE, Bhattacharya, Sehgal, Holder, Nagai 2014

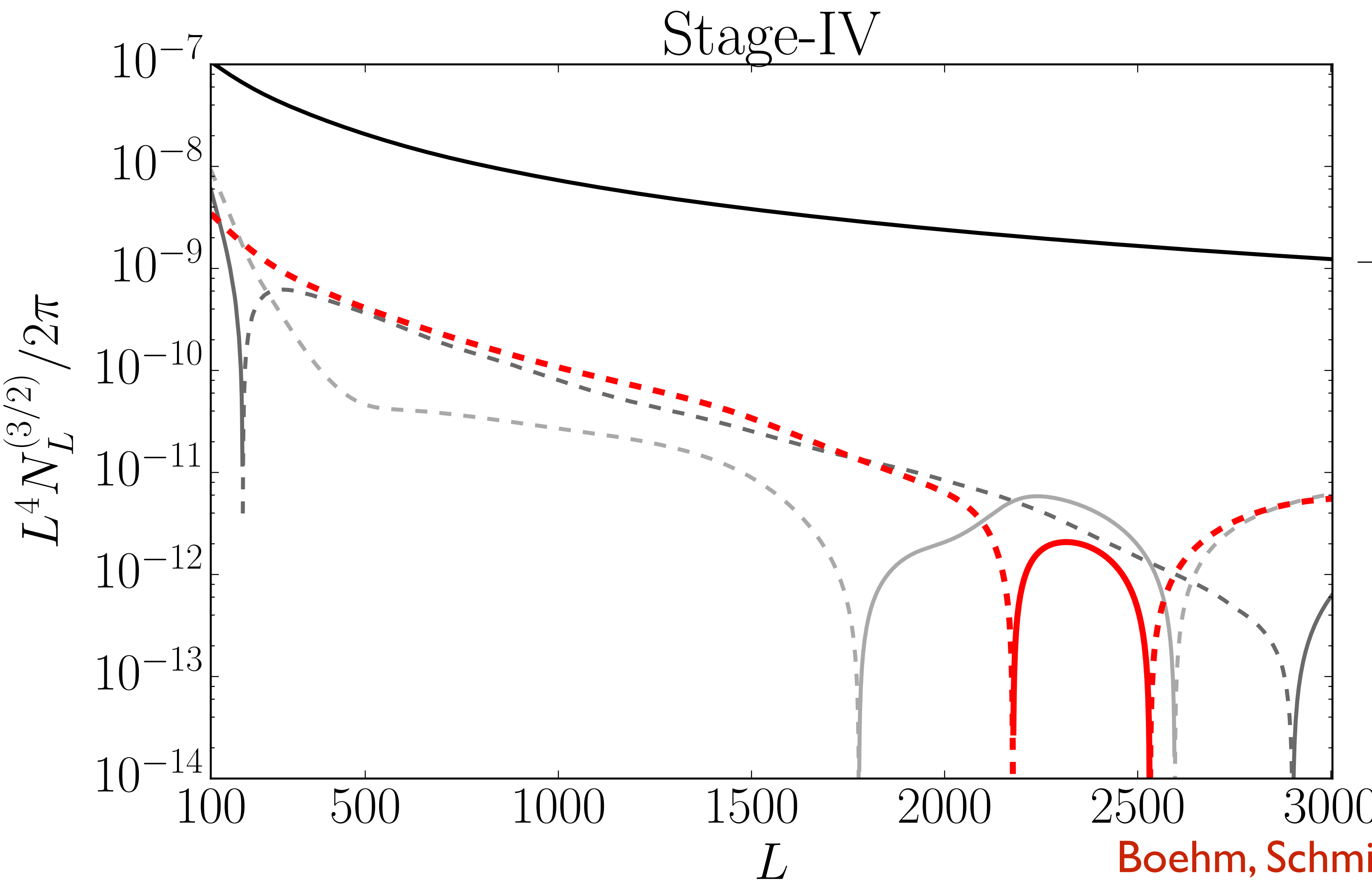
Foreground biases

How to remove?

- Use multiwavelength (AdvACT — 5 frequencies)
- Estimate bispectra of sources and project out (Osborne+ 2014)
- Use polarization, not temperature (very high-sensitivity CMB maps — Simons Observatory, CMB-S4)

non-linear growth, <κκκ>

e.g., in auto: $\langle \delta T \delta T\, \delta T' T' \rangle \sim \langle T_{,i}\phi_{,i} T_{,j}\phi_{,j}\, T'_{,k}\phi'_{,k} T' \rangle$



>1% effect in auto (tree-level bispectrum), more in sims

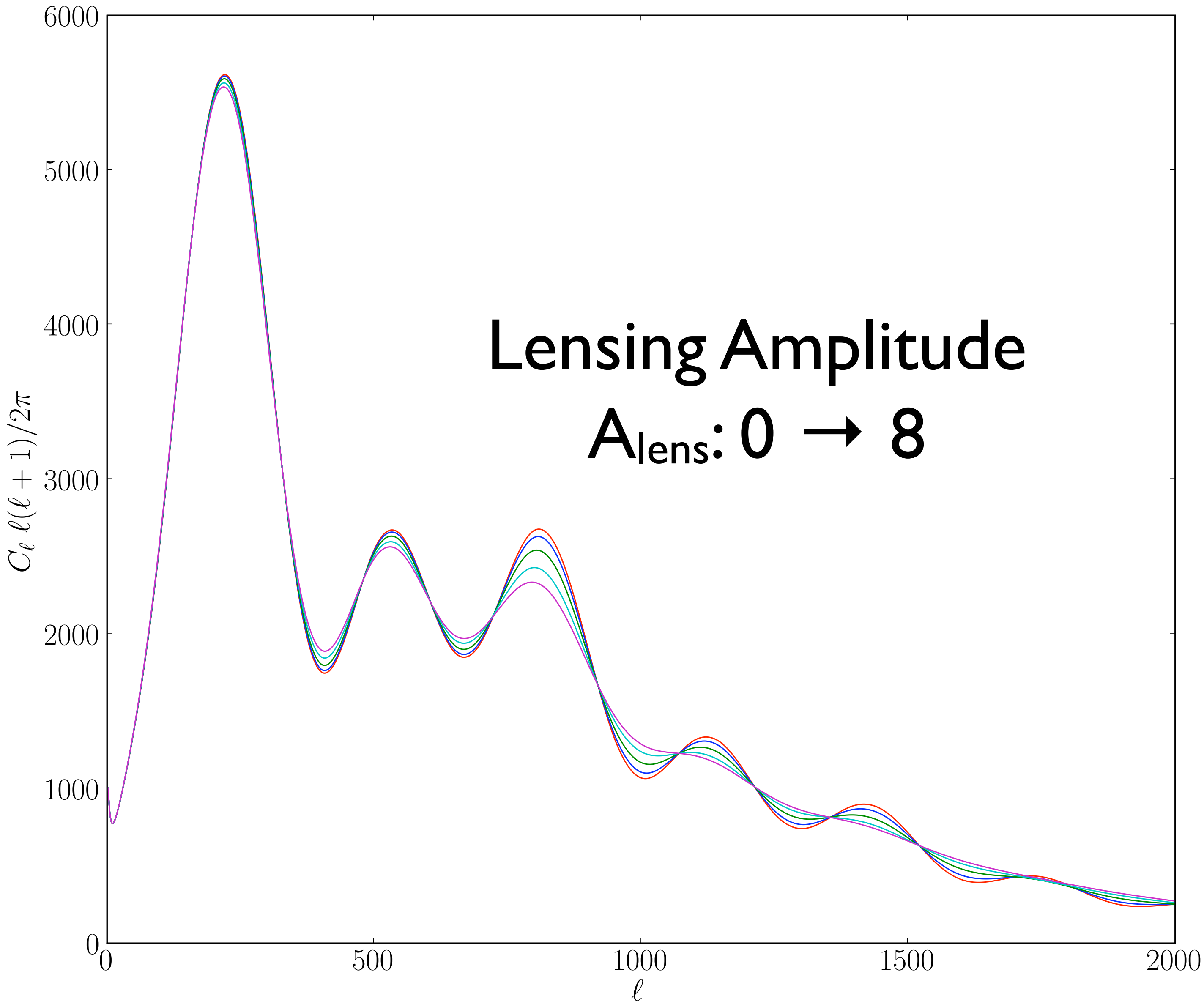
Larger for cross-corr.

Use cosmic shear to estimate??

Boehm, Schmittfull, Sherwin 2016

Also: post-Born effects: <0.2% on auto-power (Pratten & Lewis 2016, last week)

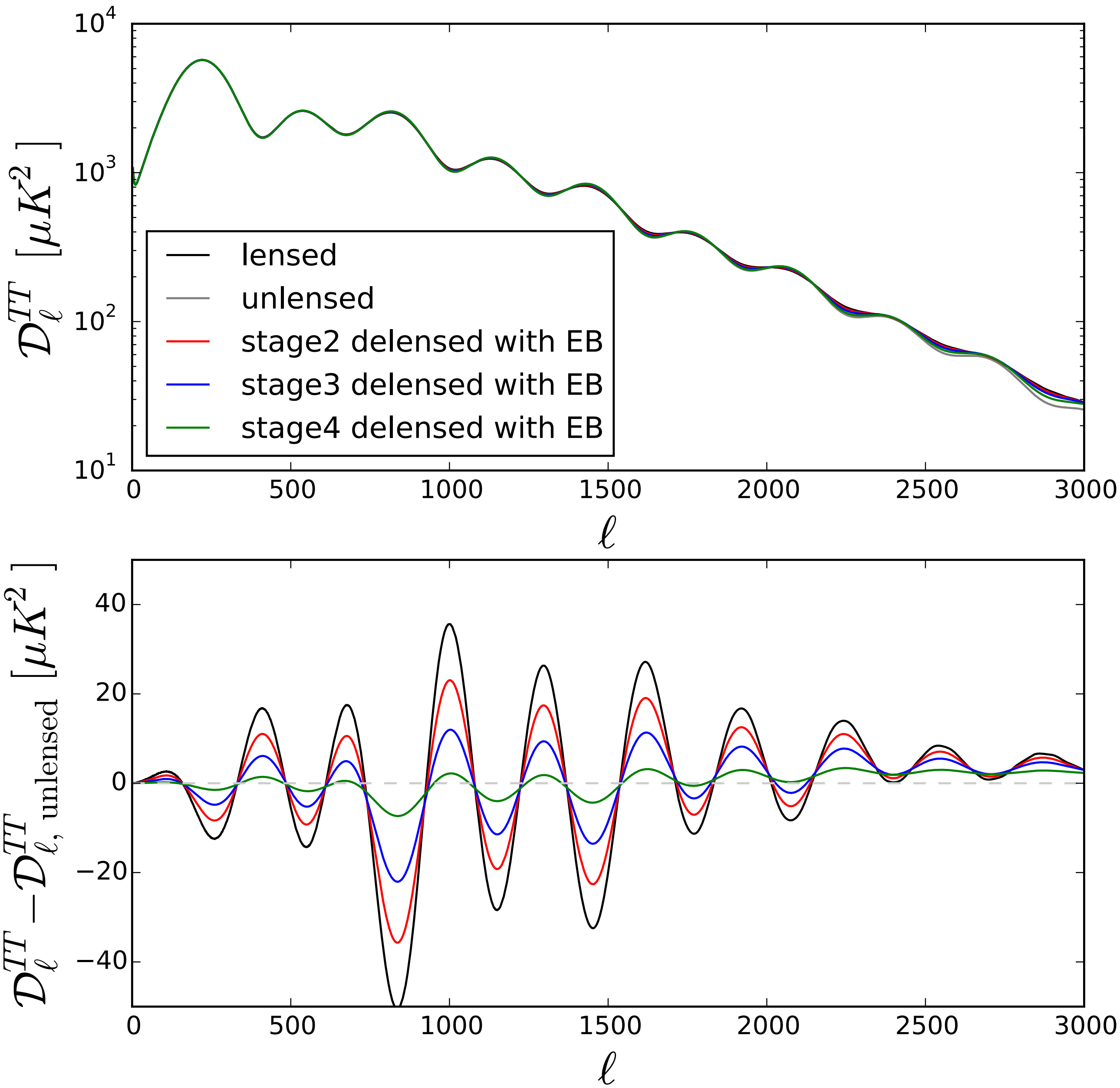
One more application:
Delensing small-scale C_l^{TT}, C_l^{EE}



Calabrese et al. (2008)

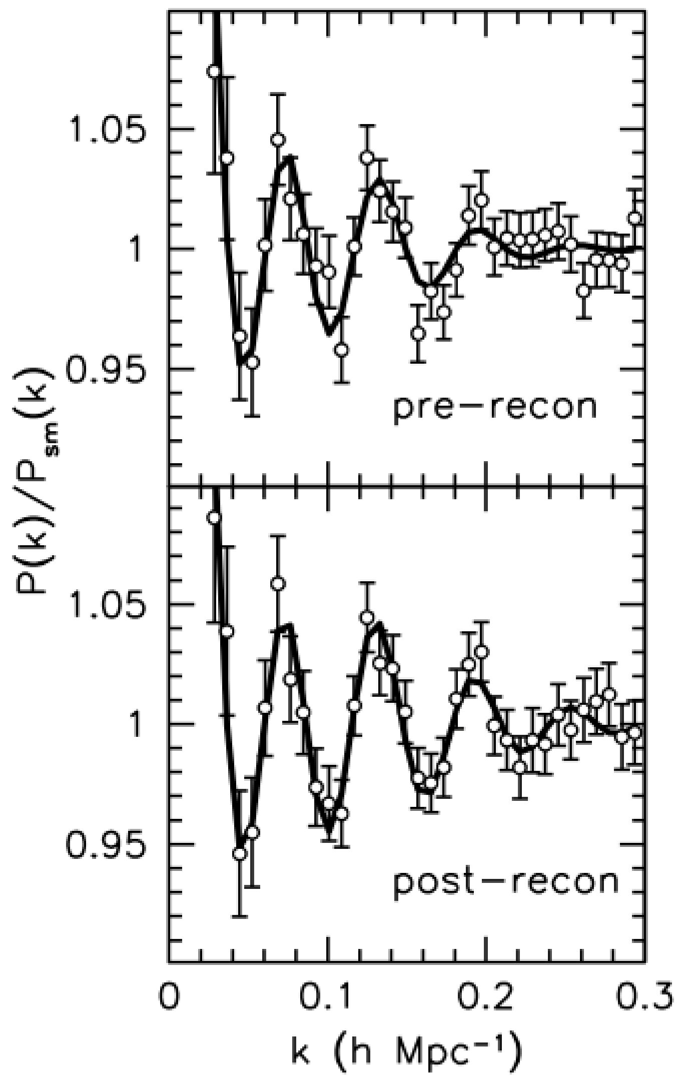
One more application: Delensing small-scale C_l^{TT}, C_l^{EE}

- Perturbative approach used in forecasting C_l^{BB} delensing is perturbative and only removes power
- We do "all-orders" correlation function-based delensing (Challinor+Lewis 2006)
- Can use any LSS map in principle (today, CIB; tomorrow, φ(EB))

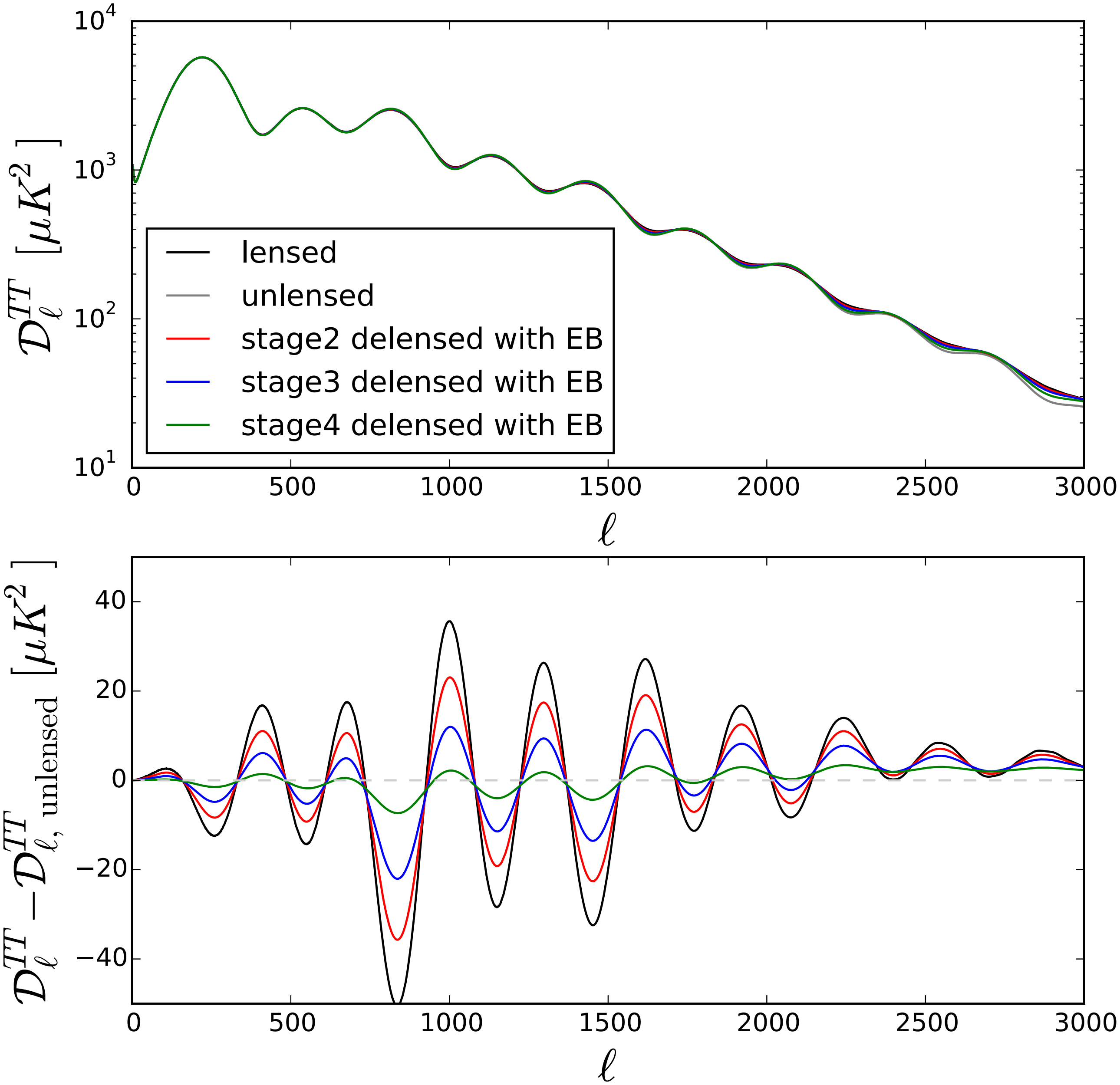


Green, Meyers, AVE 2016 in prep.

One more application: Delensing small-scale C_l^{TT}, C_l^{EE}



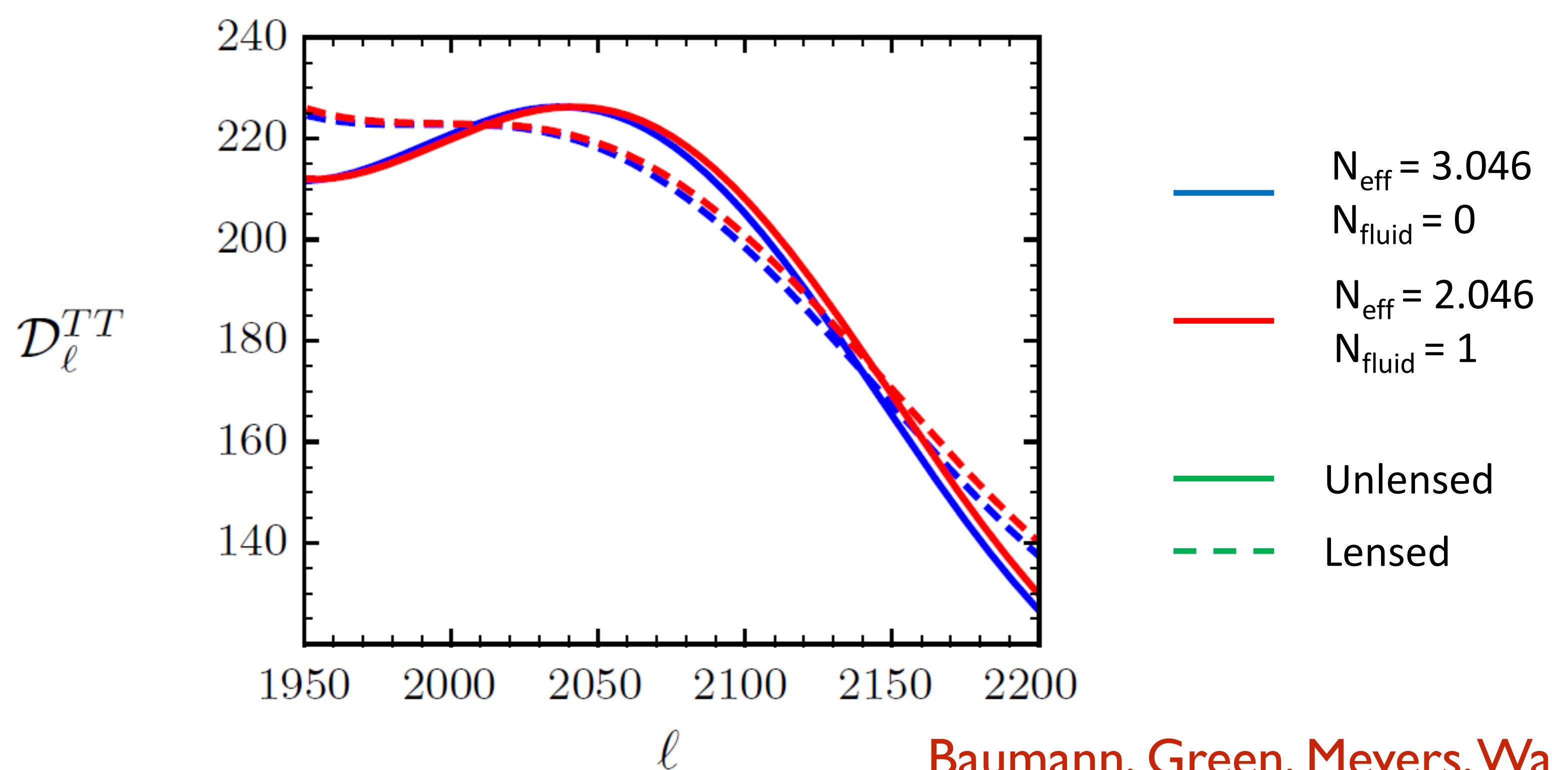
Anderson+ 2014



Green, Meyers, AVE 2016 in prep.

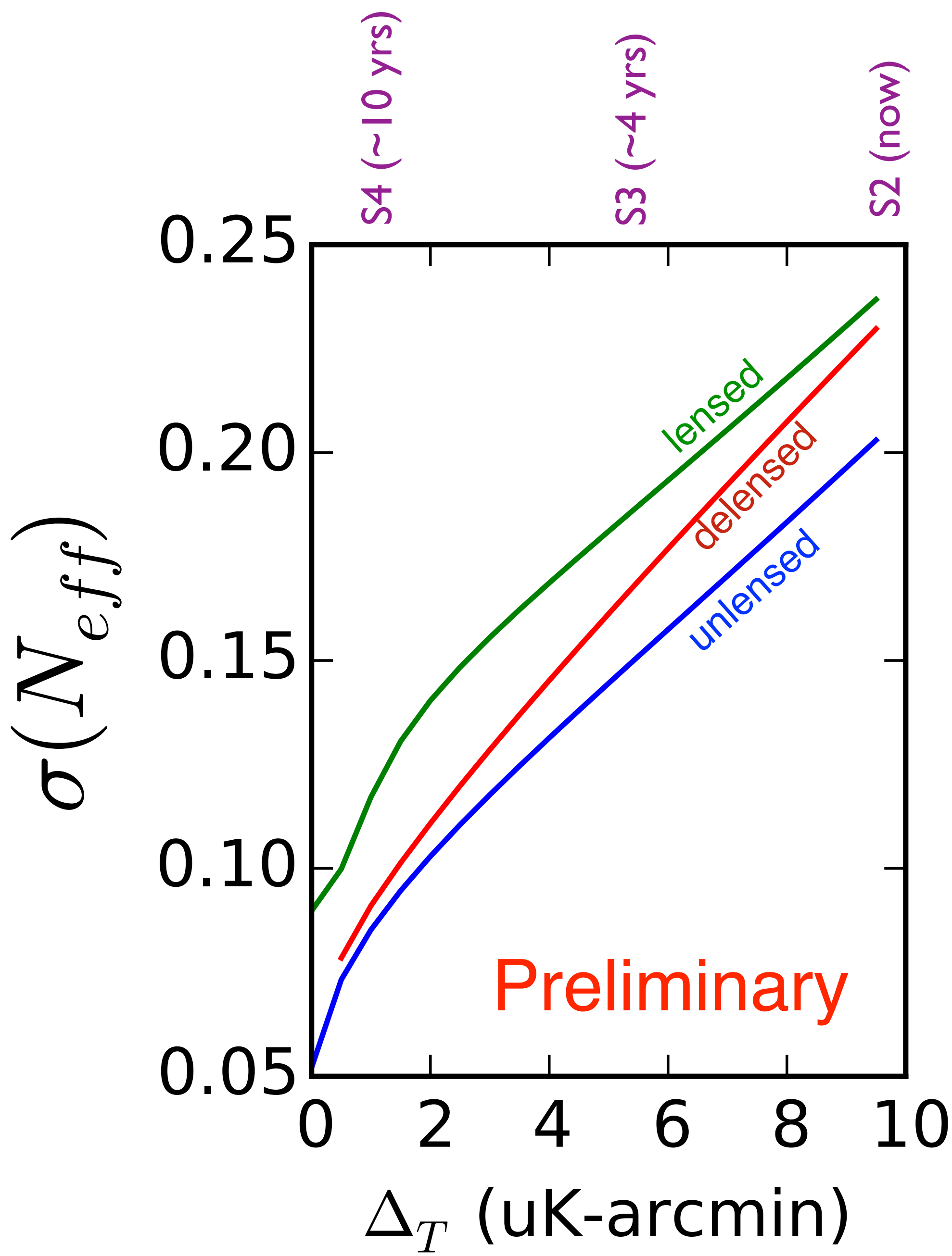
N_{eff}

- Neff defined via: $\rho_r = \rho_\gamma \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right)$ $N_{\rm eff}^{\rm CMB} = 3.04 \pm 0.18$
- ν + other ρ_r: damping
- ν + free-streaming species: phase shift in CMB acoustic peaks
  (detected with *Planck*, Follin+ 2015)



Baumann, Green, Meyers, Wallisch 2015

Forecasted constraints on N_{eff}



using C_l^{EE} data only

Theory target:
$\Delta N_{eff} > 0.027$
for massless field in equilibrium with SM

- We also include lens-induced couplings in $Cov(C_l^X, C_l^Y)$ for {X,Y} in {TT,TE,EE,κκ}

Green, Meyers, AVE 2016 in prep.

Summary

- CMB lensing is currently done with temperature and is statistical-error limited
- Current and future cross- and auto-correlations with temperature-based data may have issues with sources and with non-linear growth - 3 solutions
- Delensing high-ell *T* and *E* maps will improve N_{eff} constraints